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Anomalous Orographic Rains of O'ahu (Hawai'i) Revisited: An Over-sea Origin Indicated[1]

ALFRED H. WOODCOCK[2]

ABSTRACT: The first study of anomalous orographic rains of O'ahu, Hawai'i, utilized the average daily amounts and shower frequency characteristics as an indication of where they were first formed. In this renewed study I show that the rain rates, rather than the amounts and shower frequency, are more appropriate for revealing rain origin. Hourly amounts at gage sites alined about parallel and normal to the winds are graphically presented. The graphs reveal that many of the rains, although concentrated over the island, apparently originated as light rains over the windward sea along a crosswind line, intensifying as the wind-borne overcast of cumulus clouds was carried inland. This finding adds further support to early suggestions of an over-sea origin of many of O'ahu's orographic rains. It is hypothesized that all of these anomalous rain lines, and perhaps the trade-wind cumulus showers as well, originate upwind of the island. The idea could be readily tested experimentally.

WOODCOCK (1975) PUBLISHED observations concerning occasional orographic rains from a shallow stratocumulus overcast (SCO) falling over the Ko'olau Mountain Range (KMR) of O'ahu, Hawai'i (Figure 1). These rains, thought to be entirely warm rains, were associated with frontal passage near the island and with fresh easterly winds. They were unusual, for they were sustained and of relatively low intensity and apparently extended simultaneously in the crosswind direction over the entire length of the KMR (see Figure 2). The complete SCO cloud systems producing these rains appeared to be of the closed convection cell type (Agee et al. 1973). Their frequency has not been determined, and my observations attending their occurrence were, of necessity, incidental to travel and other activities. I have called these apparently rare rains the anomalous orographic rains (AOR) of Hawai'i, to distinguish them from the intermittent showery rains produced by northeasterly trade winds of the region (Lavoie 1974).

The original rain-recorder records show the marked difference in the nature of these rains: a smooth upward trace for the continuous AOR over the KMR (frequently confirmed visually at gage 716), and a jagged trace for the alternate shower and rain-free intervals of the scattered cumulus (e.g., see Woodcock 1975, figs. 3 and 4).

Rain gage locations, the isohyetal lines for the average daily rainfall on the AOR days (Figure 1), and the average wind velocities (Figure 3) were first regarded as strongly indicating the local orographic nature of the daily rainfall. It seemed clear that these rains must have been forming unusually rapidly, if raindrop growth and fallout occurred immediately after cloud passage over O'ahu's northeasterly shore (Woodcock 1975, section 2e). Estimates of drop growth and fallout times as low as 9 to 11 min were indicated, only a fraction of estimates during studies at other locations (Saunders 1965, Takahashi 1988).

I have long felt that further study of these rains might be worthwhile. Early work with O'ahu's orographic trade-wind showers (Blanchard 1953*b*) and recent findings—the presence of band clouds upwind of Hawai'i

[1] Manuscript accepted 15 July 1992.
[2] School of Ocean and Earth Science and Technology, Department of Oceanography, University of Hawaii at Mānoa, Honolulu, Hawai'i 96822.

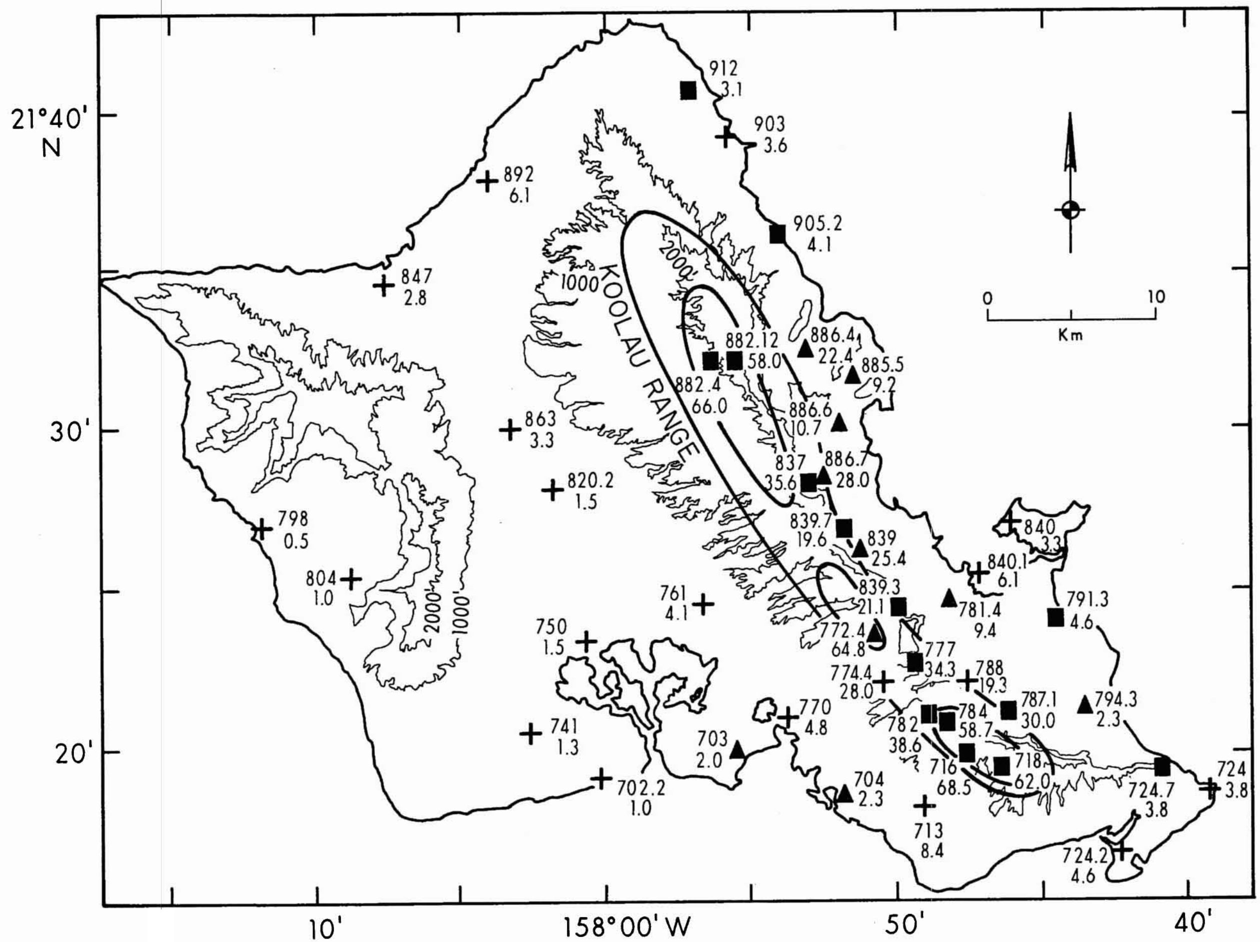
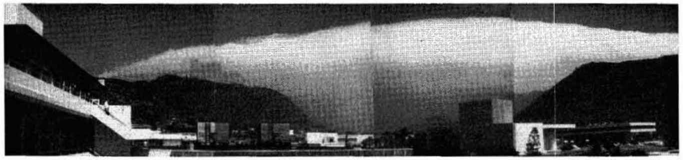


FIGURE 1. Contour map of O'ahu, Hawai'i, showing the locations of the 43 rain gages used in the earlier study (Woodcock 1975). The upper digits near these locations indicate the gage state key number, and the lower digits the gage average daily rainfall amount (mm) during the AOR days. The squares represent universal weighing or water-level recorders, the triangles represent the tipping-bucket recorders, and the plus signs represent the nonrecording gages. Isohyetal lines for the AOR amounts of 25 and 50 mm are estimated. These lines follow the well-established annual pattern over much of the KMR (Taliaferro 1959).

A



B

FIGURE 2. Photographs of AOR clouds over the KMR when northeast winds were $\sim 7\ \mathrm{m \cdot sec^{-1}}$ at cloud levels: (*A*) showing a view up Mānoa Valley looking northeast from the University of Hawaii at about 1400 hr on 23 March 1965, cumulus tops ~ 1800 m; and (*B*), showing a view in the same direction from the Ala Wai Canal (at X, Figure 4), 1000 hr on 4 December 1968, cumulus tops ~ 2100 m, when AOR was observed over a major portion of the mountain range. The valley to the left is Mānoa, and that to the right is Pālolo, where the rainfall rates at the time were 3.6 mm $\mathrm{hr^{-1}}$, while gages 882.12 and 882.4 (Figure 1) at the northwest end of the KMR showed a rate of 3.4 mm $\mathrm{hr^{-1}}$. Photographs from Woodcock (1975:336.)

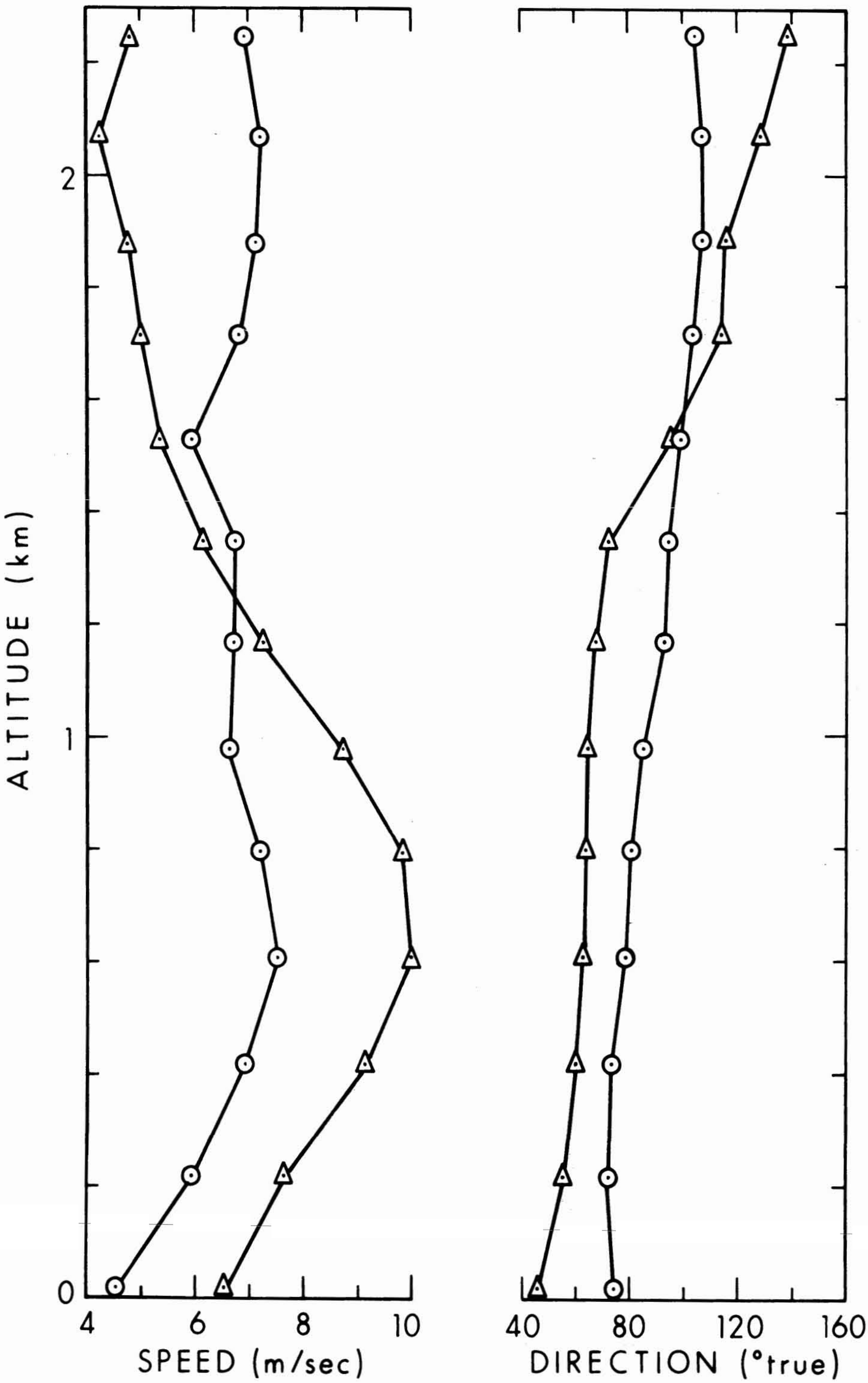


FIGURE 3. Average wind velocities in the lower atmosphere over Honolulu during the AOR days (△) compared with winds during a comparable period of trade-wind shower days (○).

(Smolarkiewicz et al. 1988) and drizzle from NE Pacific marine stratocumuli (Albrecht 1989)—were a stimulus to further effort. There was no indication, however, in the complete cumulus cloud overcast of the AOR of a band cloud structure upwind of O'ahu such as that commonly formed upwind of the island of Hawai'i.

I judged that a detailed examination of the cumulative rain gage records for the 21 AOR days might be revealing. The need was for information about the relative hour-to-hour and station-to-station differences in the rain records from the rain gages alined about parallel to the wind direction and those alined about normal to the wind direction. This information might reveal to what extent the rains were concurrent or otherwise interrelated.

MATERIALS AND METHODS

Much of the AOR observational and other material in the first paper (e.g., satellite photos of the clouds, air stability, surface weather charts, examples of rain-recorder traces, etc.) is not repeated here. This new study is focused narrowly on the argument that the relative hourly rates and occurrences of the AOR at only a few gages (i.e., Figure 4) strongly suggest an origin over the windward sea. The traditional isohyetal lines of the first study, using rain records from 43 of O'ahu's gages

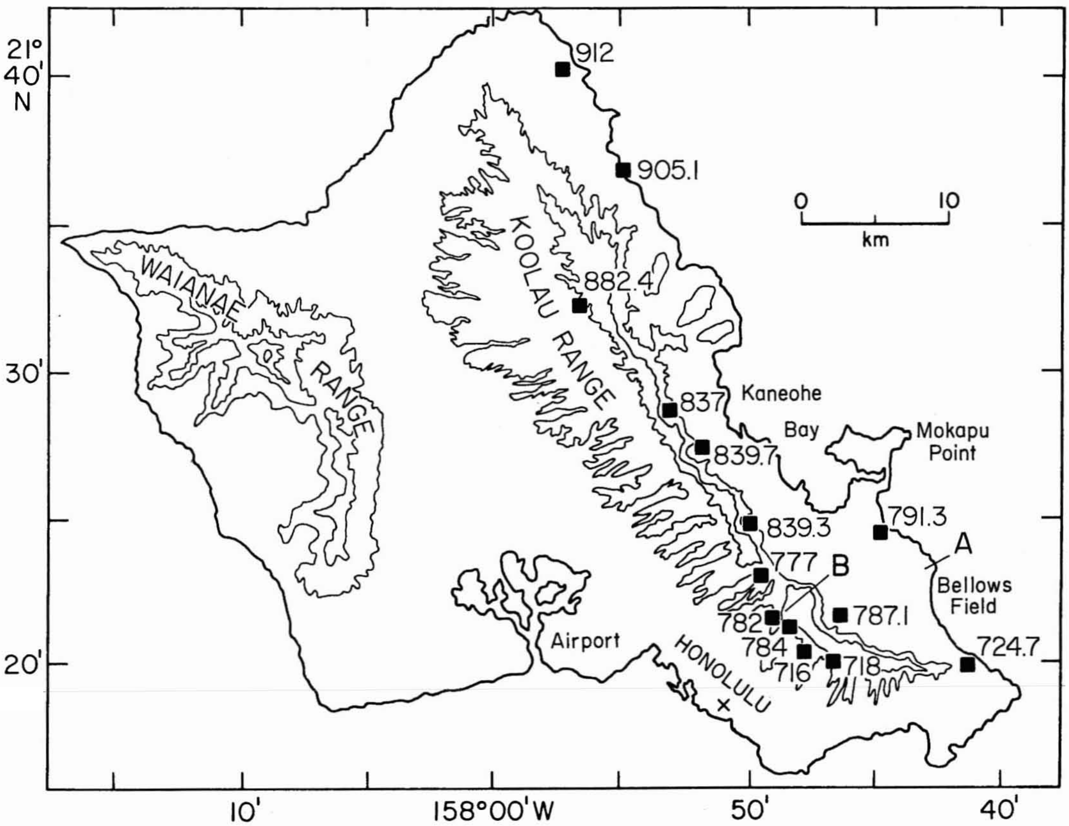


FIGURE 4. Contour and location map of O'ahu, showing sites (■) and state key numbers of the recording gages used in the renewed study of the AOR data. Sites of rain recorders used by Blanchard (1953*b*) are lettered A and B.

(Figure 1), tended to obscure the potential signs of an initiating source. Readers needing more information about ambient conditions are referred to the first effort to describe and explain these AOR (Woodcock 1975).

Rain Intensities

Daily average cumulative rain records from gages 912, 905.1, 791.3, and 724.7 at sites along the windward shore (Figure 4) represent the first rain events from the SCO carried inland by the northeasterly winds. Records from gages 837, 839.7, 839.3, and 787.1 represent subsequent rain events from these clouds a few kilometers *downwind* from the shoreline, but *upwind* from the crest of the KMR (Figure 4). Daily records from gages 882.4, 777, 782, 784, 716, and 718 represent rain events somewhat farther from the windward shore and a short distance downwind from the KMR crest (Figure 4). The data from these 14 gages represent all of the hourly rain rate information available for windward O'ahu from 21 of the 23 days listed as AOR events in Table 1 of the 1975 paper. Because of missing rain records, the 23 March 1965 and the 1 March 1967 days have been deleted here.

To investigate the potential usefulness of differences (or similarities) in hourly rain rates from site to site on O'ahu, the rain data from most of the universal or water-level-recording gages for the 21 AOR days were used. Data conversion, from the recorded cumulative rain amounts in inches per week to mm/hr, was a laborious but rewarding chore. The hourly rain intensity results thus derived were then plotted on numerous diagrams that I have called the rain intensity, location, and time (RILT) graphs. They greatly facilitated my objective—a comparison of hourly rain rates at selected gages, some alined about normal to and others about parallel to the wind direction.

RESULTS

AOR Intensity at Sites Alined about Parallel to the Wind

First, the daily RILT graphs for the 21 AOR days from the records of gages 791.3, 787.1, 716, or 718 are presented (see panels labeled "parallel," Figures 5–10). These are the only recording gages on windward O'ahu fortuitously alined, giving us three instruments about parallel to the consistent northeasterly wind direction (Figures 4 and 5–10). When these rains occur, they generally increase in duration and rate downwind, to and beyond the crest of the KMR, a distance of about 10 km. Three alined gage records are needed to show more convincingly the nature of the rain pattern change with distance inland. This can be judged by mentally eliminating gage 787.1 from the parallel panels of Figure 4–9. (For additional evidence, see tracings of the records for 24 March 1969 from alined gages 791.3, 787.1, and 716, and alined gages 905.2 and 882.4 [Woodcock 1975, fig. 4]). Gage 791.3, at the windward end of the parallel gages, is only about 0.5 km from the windward shore (Figure 4). AOR recorded there are assumed to have formed in the clouds over the sea.

AOR Intensity at Sites Alined about Normal to the Wind

Next, the daily RILT graphs for the 21 AOR days from records of gages 882.4, 777, 782, 784, 716, and 718 are presented (see panels labeled "normal," Figures 5–10). These gage records represent rain rate about normal to wind direction a short distance downwind from the crest of the KMR (Figure 4). Note that no consistent pattern of change in rain rate with distance appears in the records of the gages alined normal to wind direction, as it

FIGURES 5–10. The RILT graphs of the 21 AOR days' data are presented in the order of decreasing R, the ratio of the maximum daily number of hours rain occurred at the four coastal gages to the same quantity among the five or six gages downwind from the crest of the KMR (Figure 4). The left panels of the four daily RILT graphs on each page present rain data from the three numbered gages alined about parallel to the wind, and the right panels present data from the five or six numbered gages alined about normal to the wind (Figure 4).

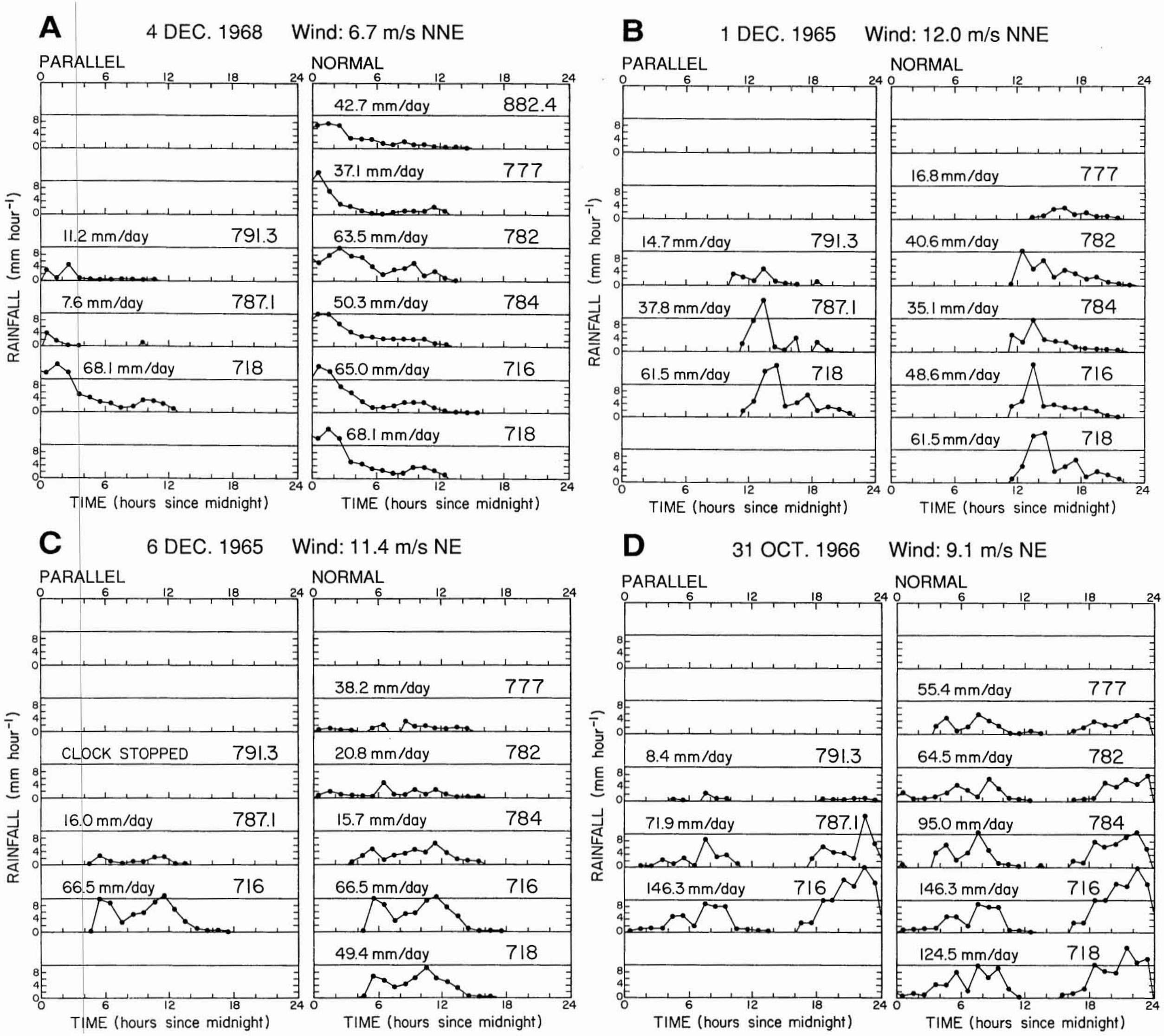

A
4 DEC. 1968 Wind: 6.7 m/s NNE
PARALLEL
NORMAL
42.7 mm/day 882.4
37.1 mm/day 777
11.2 mm/day 791.3
63.5 mm/day 782
7.6 mm/day 787.1
50.3 mm/day 784
68.1 mm/day 718
65.0 mm/day 716
68.1 mm/day 718
B
1 DEC. 1965 Wind: 12.0 m/s NNE
PARALLEL
NORMAL
16.8 mm/day 777
14.7 mm/day 791.3
40.6 mm/day 782
37.8 mm/day 787.1
35.1 mm/day 784
61.5 mm/day 718
48.6 mm/day 716
61.5 mm/day 718
C
6 DEC. 1965 Wind: 11.4 m/s NE
PARALLEL
NORMAL
38.2 mm/day 777
CLOCK STOPPED 791.3
20.8 mm/day 782
16.0 mm/day 787.1
15.7 mm/day 784
66.5 mm/day 716
66.5 mm/day 716
49.4 mm/day 718
D
31 OCT. 1966 Wind: 9.1 m/s NE
PARALLEL
NORMAL
55.4 mm/day 777
8.4 mm/day 791.3
64.5 mm/day 782
71.9 mm/day 787.1
95.0 mm/day 784
146.3 mm/day 716
146.3 mm/day 716
124.5 mm/day 718
RAINFALL (mm hour^{-1})
TIME (hours since midnight)

FIGURE 5.

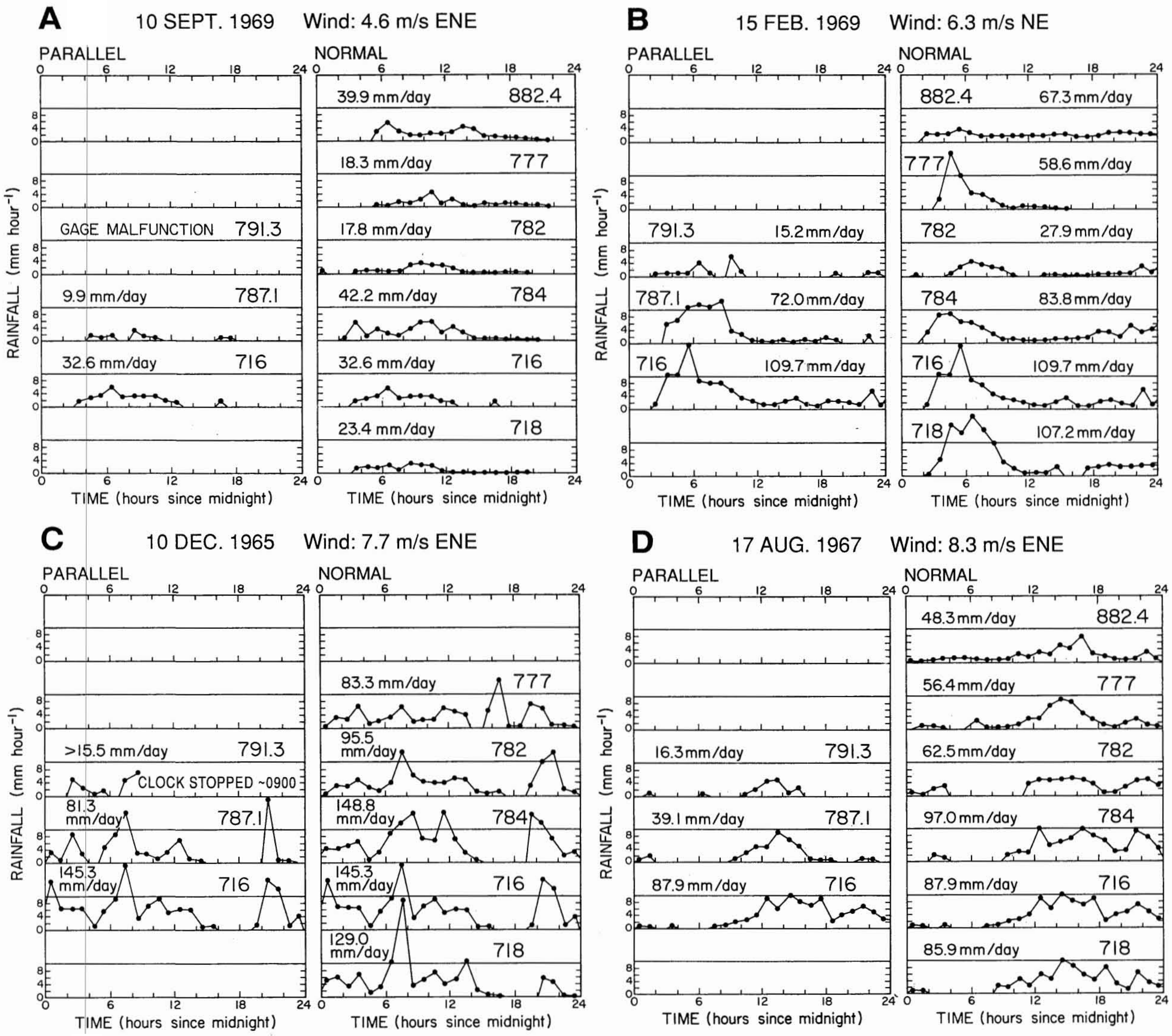

A
10 SEPT. 1969
Wind: 4.6 m/s ENE
PARALLEL
NORMAL
39.9 mm/day 882.4
18.3 mm/day 777
GAGE MALFUNCTION 791.3
17.8 mm/day 782
9.9 mm/day 787.1
42.2 mm/day 784
32.6 mm/day 716
32.6 mm/day 716
23.4 mm/day 718
B
15 FEB. 1969
Wind: 6.3 m/s NE
PARALLEL
NORMAL
882.4 67.3 mm/day
777 58.6 mm/day
791.3 15.2 mm/day
782 27.9 mm/day
787.1 72.0 mm/day
784 83.8 mm/day
716 109.7 mm/day
716 109.7 mm/day
718 107.2 mm/day
C
10 DEC. 1965
Wind: 7.7 m/s ENE
PARALLEL
NORMAL
83.3 mm/day 777
>15.5 mm/day 791.3
CLOCK STOPPED ~0900
95.5 mm/day 782
81.3 mm/day 787.1
148.8 mm/day 784
145.3 mm/day 716
145.3 mm/day 716
129.0 mm/day 718
D
17 AUG. 1967
Wind: 8.3 m/s ENE
PARALLEL
NORMAL
48.3 mm/day 882.4
56.4 mm/day 777
16.3 mm/day 791.3
62.5 mm/day 782
39.1 mm/day 787.1
97.0 mm/day 784
87.9 mm/day 716
87.9 mm/day 716
85.9 mm/day 718
RAINFALL (mm hour⁻¹)
TIME (hours since midnight)

FIGURE 6.

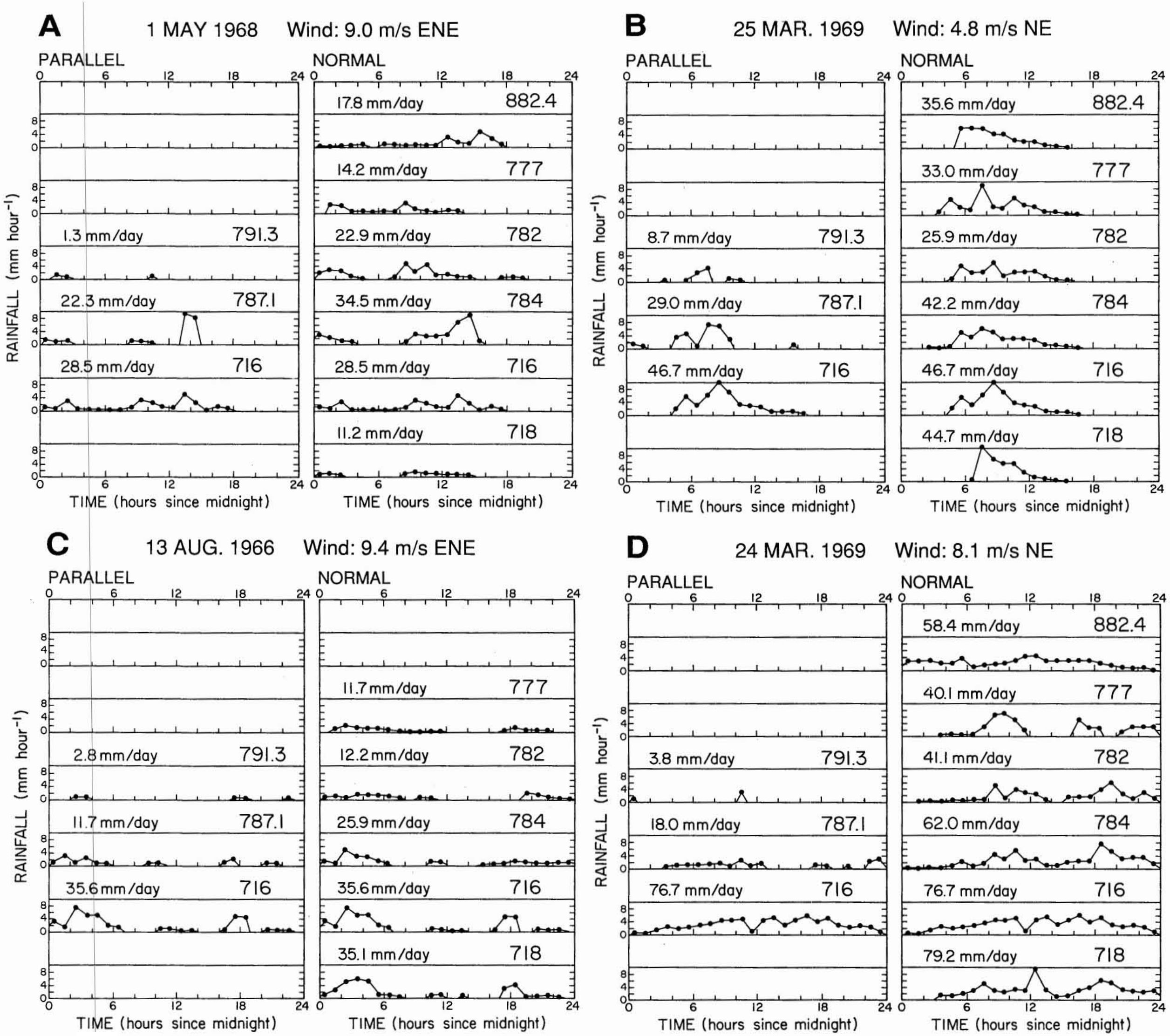
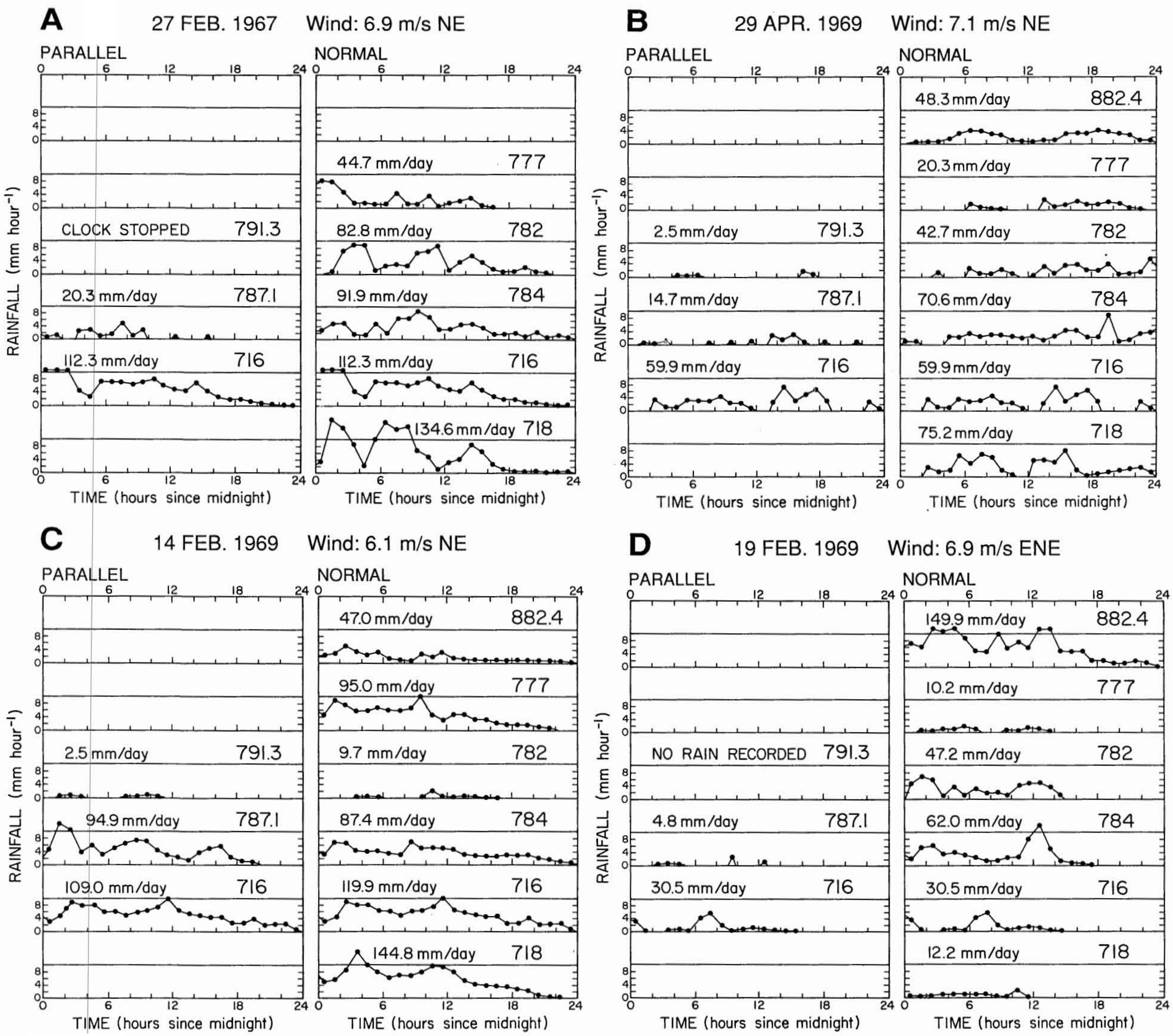

A
1 MAY 1968
Wind: 9.0 m/s ENE
PARALLEL
NORMAL
17.8 mm/day
882.4
14.2 mm/day
777
1.3 mm/day
791.3
22.9 mm/day
782
22.3 mm/day
787.1
34.5 mm/day
784
28.5 mm/day
716
28.5 mm/day
716
11.2 mm/day
718
RAINFALL (mm hour⁻¹)
TIME (hours since midnight)
B
25 MAR. 1969
Wind: 4.8 m/s NE
PARALLEL
NORMAL
35.6 mm/day
882.4
33.0 mm/day
777
8.7 mm/day
791.3
25.9 mm/day
782
29.0 mm/day
787.1
42.2 mm/day
784
46.7 mm/day
716
46.7 mm/day
716
44.7 mm/day
718
RAINFALL (mm hour⁻¹)
TIME (hours since midnight)
C
13 AUG. 1966
Wind: 9.4 m/s ENE
PARALLEL
NORMAL
11.7 mm/day
777
2.8 mm/day
791.3
12.2 mm/day
782
11.7 mm/day
787.1
25.9 mm/day
784
35.6 mm/day
716
35.6 mm/day
716
35.1 mm/day
718
RAINFALL (mm hour⁻¹)
TIME (hours since midnight)
D
24 MAR. 1969
Wind: 8.1 m/s NE
PARALLEL
NORMAL
58.4 mm/day
882.4
40.1 mm/day
777
3.8 mm/day
791.3
41.1 mm/day
782
18.0 mm/day
787.1
62.0 mm/day
784
76.7 mm/day
716
76.7 mm/day
716
79.2 mm/day
718
RAINFALL (mm hour⁻¹)
TIME (hours since midnight)

FIGURE 7.



A
27 FEB. 1967 Wind: 6.9 m/s NE
PARALLEL
NORMAL
CLOCK STOPPED 791.3
20.3 mm/day 787.1
112.3 mm/day 716
44.7 mm/day 777
82.8 mm/day 782
91.9 mm/day 784
112.3 mm/day 716
134.6 mm/day 718
B
29 APR. 1969 Wind: 7.1 m/s NE
2.5 mm/day 791.3
14.7 mm/day 787.1
59.9 mm/day 716
48.3 mm/day 882.4
20.3 mm/day 777
42.7 mm/day 782
70.6 mm/day 784
59.9 mm/day 716
75.2 mm/day 718
C
14 FEB. 1969 Wind: 6.1 m/s NE
2.5 mm/day 791.3
94.9 mm/day 787.1
109.0 mm/day 716
47.0 mm/day 882.4
95.0 mm/day 777
9.7 mm/day 782
87.4 mm/day 784
119.9 mm/day 716
144.8 mm/day 718
D
19 FEB. 1969 Wind: 6.9 m/s ENE
NO RAIN RECORDED 791.3
4.8 mm/day 787.1
30.5 mm/day 716
149.9 mm/day 882.4
10.2 mm/day 777
47.2 mm/day 782
62.0 mm/day 784
30.5 mm/day 716
12.2 mm/day 718
RAINFALL (mm hour^{-1})
TIME (hours since midnight)

FIGURE 8.

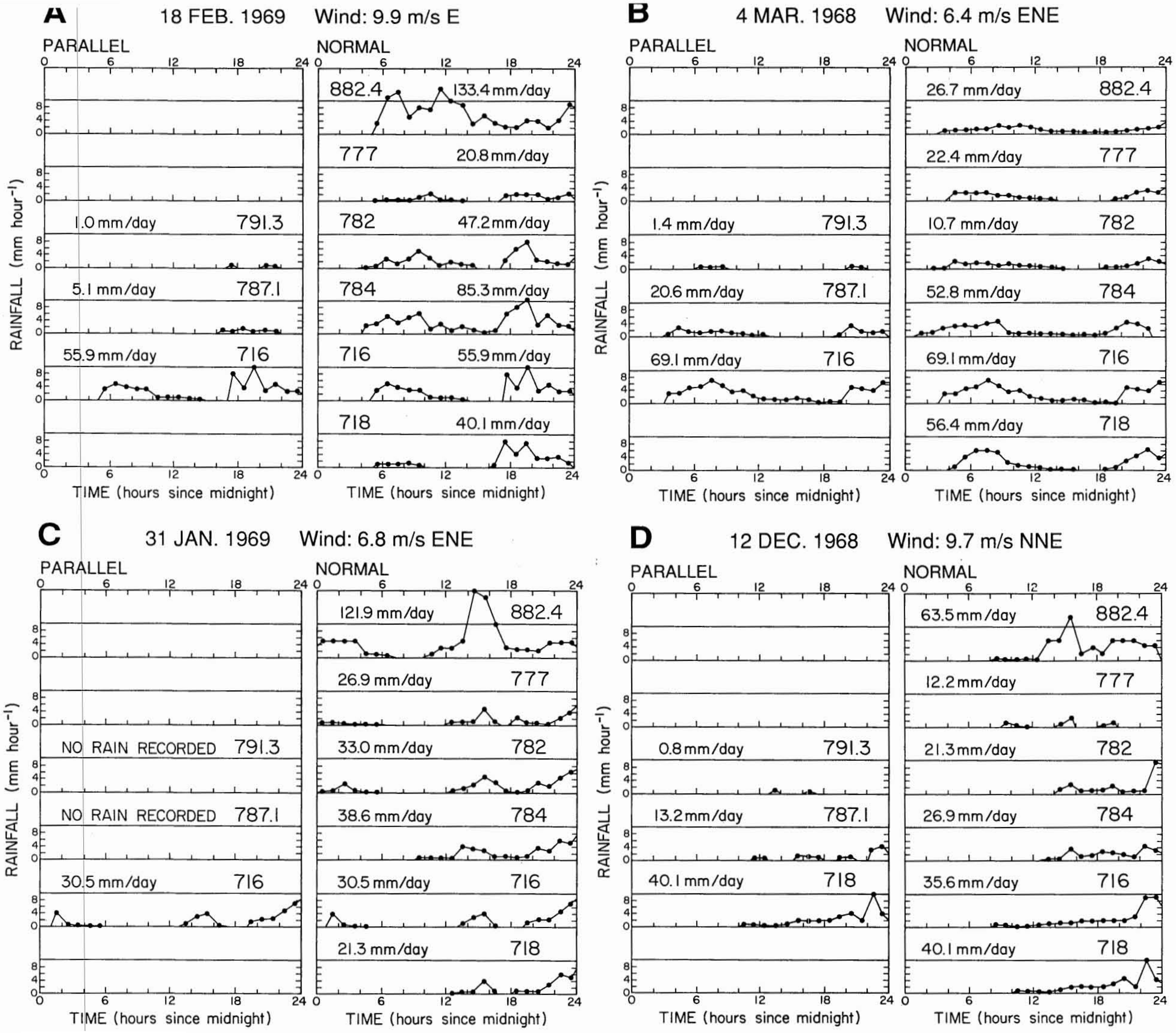

A
18 FEB. 1969
Wind: 9.9 m/s E
PARALLEL
NORMAL
882.4
133.4 mm/day
777
20.8 mm/day
1.0 mm/day
791.3
782
47.2 mm/day
5.1 mm/day
787.1
784
85.3 mm/day
55.9 mm/day
716
716
55.9 mm/day
718
40.1 mm/day
RAINFALL (mm hour^{-1})
TIME (hours since midnight)
TIME (hours since midnight)
B
4 MAR. 1968
Wind: 6.4 m/s ENE
PARALLEL
NORMAL
26.7 mm/day
882.4
22.4 mm/day
777
1.4 mm/day
791.3
10.7 mm/day
782
20.6 mm/day
787.1
52.8 mm/day
784
69.1 mm/day
716
69.1 mm/day
716
56.4 mm/day
718
RAINFALL (mm hour^{-1})
TIME (hours since midnight)
TIME (hours since midnight)
C
31 JAN. 1969
Wind: 6.8 m/s ENE
PARALLEL
NORMAL
121.9 mm/day
882.4
26.9 mm/day
777
NO RAIN RECORDED
791.3
33.0 mm/day
782
NO RAIN RECORDED
787.1
38.6 mm/day
784
30.5 mm/day
716
30.5 mm/day
716
21.3 mm/day
718
RAINFALL (mm hour^{-1})
TIME (hours since midnight)
TIME (hours since midnight)
D
12 DEC. 1968
Wind: 9.7 m/s NNE
PARALLEL
NORMAL
63.5 mm/day
882.4
12.2 mm/day
777
0.8 mm/day
791.3
21.3 mm/day
782
13.2 mm/day
787.1
26.9 mm/day
784
40.1 mm/day
718
35.6 mm/day
716
40.1 mm/day
718
RAINFALL (mm hour^{-1})
TIME (hours since midnight)
TIME (hours since midnight)

FIGURE 9.

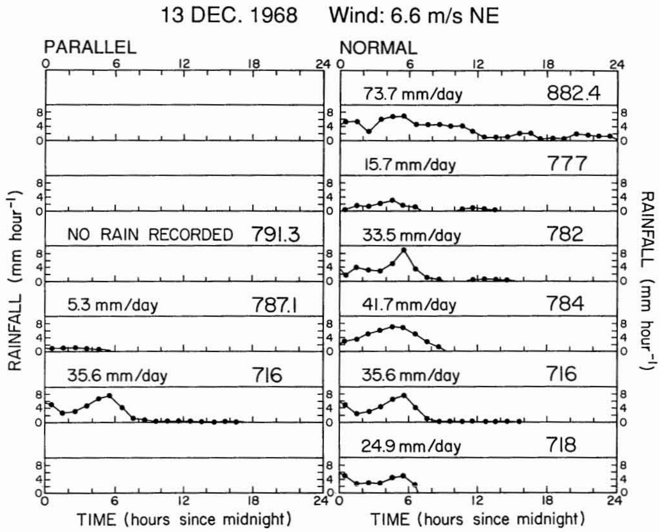


FIGURE 10.

does in the records of the gages alined about parallel to the wind (see Figures 5–10). The incidence of rain and often the direction of change in intensity is largely repeated from gage to gage over crosswind distances of 10 to 30 km.

DISCUSSION AND CONCLUSIONS

In the RILT graphs, note that on the 6 days when no rain was recorded at the upwind gage 791.3 (see Figures 5*C*, 6*A*, 8*A*, 8*D*, 9*C*, and 10*A*), the first 3 days were due to gage malfunction, leaving 18 days of complete rain record at all recorders over intersecting linear dimensions of about 10 km *parallel* to the wind and about 10 to 30 km *normal* to the wind (Figure 4).

The RILT graphs and the original rain records (e.g., see record tracings, Woodcock 1975, fig. 4) show a clear trend for rain at gages 716 or 718 to coincide with continuous rain at the other crosswind gages downwind from the KMR crest (i.e., gages 784, 782, 777, and 882.4). The graphs also show the rain at gages 716 or 718 to be preceded generally by less intense shorter-duration rains, if any, at the two upwind gages 791.3 and 787.1. The most marked exception to the latter trend was on 1 May 1968 (see Figure 7*A* "parallel," gage 787.1, time ~1400 hr). The higher rate at 787.1 than at 716 may be due to normal crosswind differences in rain rate (see Figures 5–10 "normal") and to the unavoidable misalinement of so few gages and wind direction. Gage 787.1 is more nearly ENE of gage 784 and is actually almost NE of gage 716, with which it is being compared.

The discontinuous nature of the coastal rains at gage 791.3 is tentatively interpreted as an effect of a line source of continuous (light) rain within the cloud stream that is parallel to the KMR and a short but variable distance upwind of O'ahu—"continuous" because the continuous AOR over the crest of the KMR imply a continuous upwind line source, and "light" because that is the trend of the rain records. Only the more intense parts of these rains are thought to be detected by the coastal gages, before being carried inland by the frequent fresh winds (see Blanchard 1953*b*: 536, on problems of sampling and recording O'ahu's light rains).

Rain at the windward shore is usually attended by rain downwind over O'ahu, with duration downwind increasing, resulting in relatively uninterrupted rain over the KMR.

However, obviously, the reverse is not true, although there are many occasions when rain over the KMR is not attended by rain at the shore site.

This apparent paradox is explained as follows. Among orographic rains sampled near cloud base in Hawai'i, intensity has been found to be directly related to drop size (Blanchard 1953*a*, fig. 3). Because drop size is directly related to fall speed, the lower-intensity AOR (i.e., those ≤ 1 mm/hr), such as many of those on windward O'ahu (see Figures 4–9, "parallel" panels), will be expected to have median volume diameters (which divide the drop size distribution into two parts, each containing one-half of the water content of the rain) of about 0.4 mm (Blanchard 1953*a*, fig. 13) and fall speeds of 1.6 m/sec (Gunn and Kinzer 1949). For example, one would expect that if continuous rains of 1 mm/hr are initiated at about 1.5 km altitude in the clouds over the sea (1.8 km was the average cloud-top altitude observed), they might often be carried inland beyond gage 791.3 by the winds (see Figure 4) during the 15 min required for the 0.4-mm-diam. drops to reach the surface. Thus the absence of rain at the upwind gages can be interpreted as an indication that the hours of missing rain at shore gage 791.3 are hours when rain was passing inland overhead and had yet to arrive at the surface. On 1 day, recorded rain was limited to the downwind gage 716 alone (see Figure 9*C*).

It can be argued that simple coincidence alone may explain the occurrence of rain at the downwind and upwind gages alined about parallel to the wind. If so, we would then need to explain why chance would usually produce the observed less-intense rains in the upwind direction among the *parallel* gages.

The occurrence of an offshore linear origin of these rains is precisely one of the alternatives I rejected in my 1975 paper as "highly unlikely" (Woodcock 1975:335). Clearly, there is something in the SCO that does, on some occasions, prepare it to produce rain upwind of the island, and to do so apparently simultaneously along a 30-km line about parallel to the KMR.

One can speculate that a dynamic lifting of the airstream upwind of O'ahu, such as that indicated for the island of Hawai'i (Smolarkiewicz et al. 1988), may be the cause of the initiation of rain in these clouds. Or, alternatively, perhaps the marine SCO produces continuous light rain or drizzle (Albrecht 1989) that sometimes extends over large areas and is often undetectable by the coastal gage.

However, the primary purpose here is to present the evidence of a linear origin of the AOR upwind of O'ahu. This is a useful next step in understanding these rains, irrespective of the various possible mechanisms that may explain how and why they form over the windward sea. It will be good to discover what warm cloud drop growth processes in the marine boundary layer can explain this apparent extensive simultaneous production of continuous rain.

It is evident that there are rather marked crosswind differences in rain rate with time and distance (see Figures 5–10, "normal" panels). Because the AOR are apparently initiated at sea, these differences are tentatively attributed to changes in the vertical dimensions and liquid water contents of the SCO, which is apparently made up of closed convection cells.

The formation of O'ahu's orographic showers in the scattered cumulus of the more-frequent northeasterly trade-wind conditions may also begin in the cumulus clouds over the windward sea. Blanchard (1953*b*) showed that during the trade winds about three times more showers occurred at site B near the KMR ridge at the head of Mānoa Valley than at Bellows Field, about 10 km upwind at the shoreline site A (see Figure 4). He used a dyed paper tape method, recording all showers with drops greater than about 0.1-mm diam. at the two sites, over a period of 6 days. Cautioning the reader about these differences in shower number at the two recorder sites, Blanchard said, "It should not be inferred from this that the majority of the showers completely develop during the time it takes the clouds to travel between the two recorder stations. It seems probable, as already discussed, that many of the clouds have already developed to the drizzle stage by the time they pass over the windward recorder" (Blanchard 1953*b*:536).

Thus Blanchard recognized the problem of explaining O'ahu's orographic trade-wind showers, assuming complete development in the clouds while passing over only ~10 km of the island. He suggested that the missing light windborne showers had yet to reach the surface and were simply passing inland in the air stream above recorder A at the windward shore. I have made a similar suggestion here to explain the difference between the windward coastal and downwind AOR, but with the notable addition of the evidence of a simultaneous initiation of an extensive crosswind line of rain, at least 30 km long, that seems pre-oriented parallel to a major geological feature of O'ahu, the great erosional cliff (locally called "the Pali") of the 35-km-long NE face of the KMR (Stearns 1985).

Recommendations

Radar precipitation studies are needed on O'ahu to determine more clearly where and when raindrops first appear in the windborne marine cumulus clouds (both scattered trade-wind cumulus and SCO) as they approach the island and pass over the KMR. For continuous monitoring, more long-term evidence is needed on the usual areas of origin of the KMR rainfall. A better distribution of rain recorders, located about parallel to the prevailing easterly winds in the Mōkapu Point–Bellows Field areas (Figure 4), should fill this need.

From the distribution of rain intensity over windward O'ahu on the AOR days, it is concluded that *many* of these rains when first formed were in the SCO over the sea, along a crosswind line at least equal in length to the KMR. Rains from this offshore shower line are generally light, increasing in rate as the wind carries the clouds inland over O'ahu and the KMR. It is hypothesized that *all* of the AOR originate over the windward sea and perhaps many of the trade-wind showers as well.

Thus, the earlier idea that these AOR reveal "an unusually rapid rain generation process occurring in the strato-cumulus clouds over Oahu" (Woodcock 1975:342) has now become highly questionable.

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